Technical Report No. 32-848

Large Antenna Apertures and Arrays for Deep Space Communications

Philip D. Potter

William D. Merrick

Arthur C. Ludwig
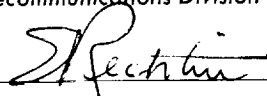
W.D. Merrick

W. D. Merrick, Manager
DSIF Engineering Section

P. D. Potter

P. D. Potter, Manager
Communications Elements Research Section

W. K. Victor

W. K. Victor, Manager
Telecommunications Division

E. Rechtin

E. Rechtin, Assistant Laboratory Director
for Tracking and Data Acquisition

CONTENTS

TABLES

FIGURES

ABSTRACT

/0/2/

Three considerations relating to antennas for deep space communications are treated in detail: (1) the economic balance between large ground antenna apertures and potential spacecraft improvements, (2) the best method of implementing large apertures as a function of size, and (3) the optimum frequency of operation. To answer these questions this Report concentrates on economics, because there do not appear to be any serious technical problems that cannot be obviated by proper design of the ground station. Three conclusions are firmly established: (1) equivalent apertures, large compared with that of a 200-ft-diam class paraboloid, are very expensive and not economically warranted for another 10 to 15 years, at which time a manned planetary exploration program may exist; (2) either a steerable paraboloid of approximately 200-ft diameter or an array of these antennas is the ideal type of aperture implementation; and (3) within the present state of the art in structural design the optimum frequency of operation is approximately 2 Gc/s—however, a significant improvement in structural techniques could make the 4 to 6 Gc/s band more attractive.

I. INTRODUCTION

A. NASA Communications History

Communications is clearly a vital factor in the space program; therefore, the National Aeronautics and Space Administration (NASA) has maintained a consistent and balanced program of development in all critical areas to improve communications capability. The history of this development may be traced back to the 14-lb *Pioneer IV* probe, which was launched in 1959 with a transmitter power of 0.27 W and an antenna gain of 2½ dB. If we measure performance in terms of the data rate at a distance of 1 AU (93,000,000 mi), *Pioneer IV* could have transmitted 0.00025 bits/sec to a ground

station with an 85-ft antenna and a receiving system temperature of 1450° K.

Three years later, in 1962, the 450-lb *Mariner* Venus spacecraft utilized a 3-W transmitter and an antenna with 19 dB gain. At a distance of 1 AU, the *Mariner* Venus spacecraft could have transmitted 0.7 bits/sec to a ground station with an 85-ft antenna and with a receiving system temperature of 250° K. The factor of 2,900 increase in data rate was achieved by improving the spacecraft by a factor of 500, and the ground system by a factor of 5.8.

Three years later, in 1965, the 575-lb *Mariner* Mars spacecraft was capable of transmitting 34 bits/sec at a distance of 1 AU, a factor of 47 improvement over the *Mariner* Venus spacecraft and a factor of 136,000 improvement over the *Pioneer IV* probe. The enhanced communication capability was again achieved by an improvement in both the spacecraft and ground systems. The spacecraft transmitter power was 10 W, and by operating at a higher frequency, 2290 Mc/s instead of 960 Mc/s, the spacecraft antenna gain was 24 dB, a factor of 10.5 spacecraft improvement. The ground system temperature was 55°K, or a factor of 4.5 improvement.

Looking into the future, one should expect *Voyager* spacecraft in 1971 to transmit 12,000 bits/sec at a distance of 1 AU. This improvement might be expected with increases in performance of both the spacecraft and ground system equipment. The spacecraft transmitter power could be increased to 50 W with an antenna gain of 32 dB, while the ground system, with the use of a network of 210-ft-diam antennas, could operate with a gain of 61 dB and 25°K. The combined improvements of the spacecraft and ground equipment would provide a factor of 360 increase in deep space communications capability over that of the *Mariner* Mars spacecraft. This information is summarized in Tables 1 and 2.

One interpretation of Table 2 is that the total amount of information received from a mission is limited by the communications data rate; however, this is not always true. In a balanced design, other factors will be equally important. For example, the NASA/JPL *Mariner* Mars television experiment was, also, limited by the storage capacity of the tape recorder on the spacecraft; simply an increase in communications data rate by a factor of 10 would not have provided ten times as many pictures of the Martian surface. The number of pictures was limited to 21 by the size of the tape recorder, and an increase in communications data rate would have resulted only in returning the information ten times as quickly.

Although not shown in Table 1, the ability to execute reliable command of spacecraft at steadily increasing

Table 2. Communications system parameters

Data signal characteristics	Transmitter parameters	Transmission media	Receiver parameters
Data rate ↓ $R_v = K$ ↑ Data quality, losses, etc.	Transmitted power ↓ $P_T\, G_T\,(f)$ ↑ Gain of transmitting antenna	$\dfrac{1}{f^2\; R^2}$ ↑ Frequency Transmission distance	Gain of Receiving antenna ↓ $\dfrac{G_r\,(f)}{T_r\,(f)}$ ↑ Receiver-noise temperature
	×	×	×

Table 1. Development of communications capability, telemetry link

Program	Spacecraft parameters[a,b]		Frequency of operation, Mc/s	Ground system parameters[b]		Data rate[c] at 1 AU, bits/sec
	Transmitter power P_T,W	Transmitter gain G_T, dB		Recvr. antenna gain G_r, dB	Recvr. noise temp. T_r, °K	
1959 *Pioneer IV*, 14 lb	0.27	2½ (Single-element antenna)	960	46 (85-ft diam)	1450	0.00025
1962 *Mariner II*, 450 lb	3	19 (4-ft diam)	960	46 (85-ft diam)	250	0.7
1965 *Mariner IV*, 575 lb	10	24 (3-ft diam)	2290	53 (85-ft diam)	55	34
1971 *Voyager*[d], 7000 lb	50	32 (7-ft diam)	2290	61 (210-ft diam)	25	12,000

[a] −7 dB losses (system, pointing, negative tolerances, etc.). Half of radiated power in sidebands.

[b] Antenna efficiencies 55%.

[c] Bit error probability $P_e{}^b = 10^{-5}$ (coherent phase-shift-keyed).

[d] Pre-design estimate.

distances has also been accomplished in the same time period.

B. Purpose of the Report

The primary concern of this Report is the ground station. In particular, we are concerned with (1) the economic balancing of ground antenna aperture size with potential improvements in spacecraft performance, (2) the best method of achieving this aperture, whether by a single antenna or by an array of antennas, and (3) the optimum frequency of operation.

These considerations were studied at JPL during the period from 1960 to 1962 when it was apparent that increased communications capability would soon be required. The studies resulted in the specifications for the 210-ft diam NASA/JPL Advanced Antenna System, AAS (Ref. 1). The first of these antennas is now near completion at Goldstone, Calif. Costs of this size of antenna, which are now well established, agree with the estimated costs in the definitizing study; and preliminary indications are that the performance of the antenna will meet the original specifications. With these data now available and, also, with the additional information on spacecraft performance and characteristics, there is a good basis for re-examining the above considerations for even longer-range requirements.

It is important that the program sponsored by the NASA during the past six years to effect balanced development between the ground station and the spacecraft be continued. Excessive development of ground stations could absorb such a large percentage of the available funding that the number of spacecraft launched would be severely limited. Conversely, excessive development of the spacecraft at the expense of the ground stations would markedly reduce the amount of data that could be collected from each flight. In a well balanced program, it would be found that an additional dollar invested in the ground stations would provide an increase in returned data, integrated over the useful life of the stations, that would be exactly the same as an increase in data resulting from an additional dollar invested in spacecraft development. Deviations from this desired balance imply either less data for a given amount of money or more money for a given amount of data. Clearly, many factors are involved which are complicated by the dynamic nature of spacecraft program technology and long development lead times; therefore, a perfect balance may not be practical. However, because of the large sums of money involved, it is impera-

tive to maintain the continuing analysis of trade-offs involved so that an optimum balance may be approached as closely as possible.

The factors involved in creating a balanced program were recognized early in the development of the NASA/JPL Deep Space Network; as a consequence, the economic analyses considerably affected the development. This is the first formal, generally distributed report of such studies.

C. Basic Deep Space Communications Requirements

Several of the features presented for the design of stations for deep space tracking and data acquisition are considered mandatory. The first such requirement is for antenna operation under all reasonably anticipated weather conditions at the Deep Space Network sites, which are near Goldstone, California; Madrid, Spain; and Canberra, Australia (the three sites which will utilize the 210-ft antenna). Antennas to satisfy these specifications cost approximately 1½ times as much as similar radio astronomy antennas, which do not require this degree of operational reliability. However, since the antenna cost is only a fraction of the overall ground station costs, the net difference in total cost is less than the factor of 1½; in any case, it is small when compared with the costs of a spaceflight mission aborted because of weather conditions. All-weather reliability also has a strong effect on the selection of operating frequencies, as will be shown later in the Report.

The second mandatory requirement is for continuous, 24-hr/day communications with spacecraft in deep space. To meet this need, three deep-space stations per network are located approximately 120 deg apart in longitude around the Earth; two stations would not provide adequate coverage, and more than three are unnecessary. If the continuous communications capability were not to exist, mission penalties would be imposed in the form of increased spacecraft weight, complexity, and lower reliability as a result of the necessity for increased data storage; in some cases, such data-storage demands might exceed the capacity of existing storage devices. Another disadvantage of broken communications is the possible loss of information on the cause of spacecraft failure during a non-view period. Of even greater importance, a discontinuous operation would prevent taking full advantage of the flight-demonstrated, highly successful and proven technique of continuous contact with a continuously operating spacecraft.

The third requirement is for both a low-gain/broad-beam and a high-gain/narrow-beam communication link. While the necessity for a high-gain link for maximum data rates is fairly obvious, the need for low-gain/broad-beam link may be less so. However, Earth command requisite can exist when the high-gain antenna is not pointed at the Earth, either during vehicle maneuver or vehicle malfunction. An example is the recent experience of *Mariner IV* losing roll-attitude lock on the reference star Canopus and locking on other stars instead, until commanded back to the proper reference. Other conditions when the omnidirectional or low-gain link is also required are (1) for telemetry during spacecraft maneuvers when the high-gain antenna cannot be aimed at the Earth, (2) for transmitting failure telemetry in the event of attitude control malfunction, and (3) for telemetry from landing capsules or spinning spacecraft for which a steerable antenna might not be practical.

II. EFFECT OF FREQUENCY ON COMMUNICATIONS CAPABILITY

A. Physical Perturbations and Gain Limit

Several physical effects can cause phase errors in the aperture of an antenna. Either an error in antenna pointing or a large scale distortion of an incoming wavefront will cause a primarily linear phase error. Mechanical deflections and manufacturing tolerances cause deviations in the reflector surface which result in a more or less random phase error. The latter effect is also produced by small scale distortions of an incoming wavefront. All of these effects cause a gain loss given by an equation of the same general mathematical form. If we define σ_p as the path-length error at the edge of a paraboloid, relative to the center of the paraboloid, caused by pointing-type errors, and σ_m as the rms path-length error due to random-type errors, we can then define a net error $\sigma^2 = \sigma_p^2 + \sigma_m^2$. The net-gain-loss is then given (see Ref. 2) by:

$$\frac{G}{G_0} = \exp - \left(\frac{4\pi\sigma}{\lambda}\right)^2$$

where λ is the free-space wavelength at the operating frequency. This is not necessarily an exact form for the pointing-error loss, but may be used for the overall situation without gross error.

If the above equation is combined with the equation for the phase error-free gain of a paraboloidal antenna of fixed physical area, which is proportional to f^2 or $1/\lambda^2$, it is found that, at a certain frequency, the rate
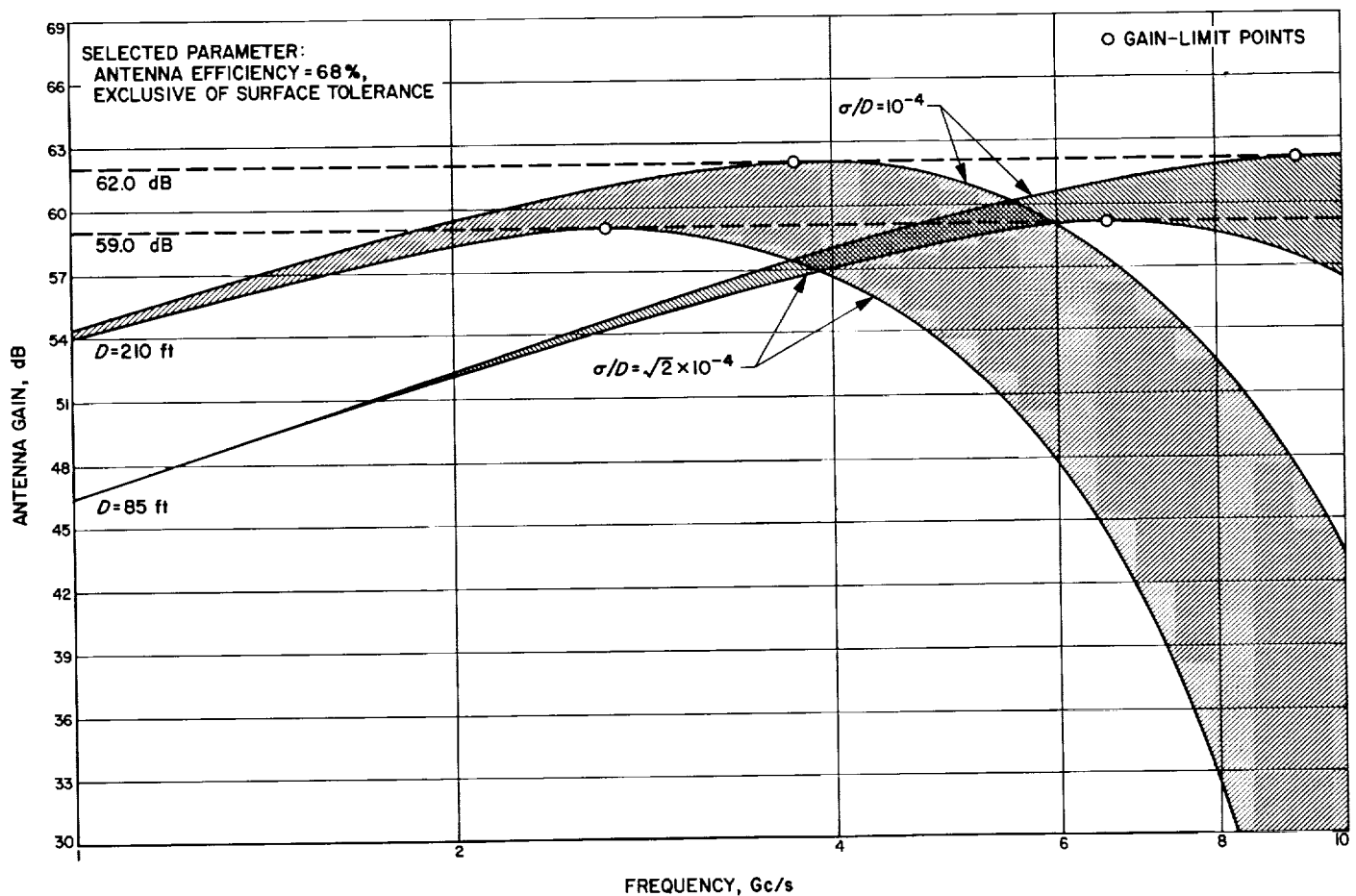

Fig. 1. Gain vs frequency, size and surface tolerance for one ground antenna

of gain loss due to phase errors overcomes the rate of gain increase due to the f^2 term; this is the gain-limit point of the antenna. The gain at this point, regardless of the functional dependence of σ, is inversely proportional to $(\sigma/D)^2$, where D is the diameter of the antenna. This effect is illustrated in Fig. 1. At gain limit, for σ/D = constant, antenna diameter and frequency are inversely proportional, as shown in Fig. 2.

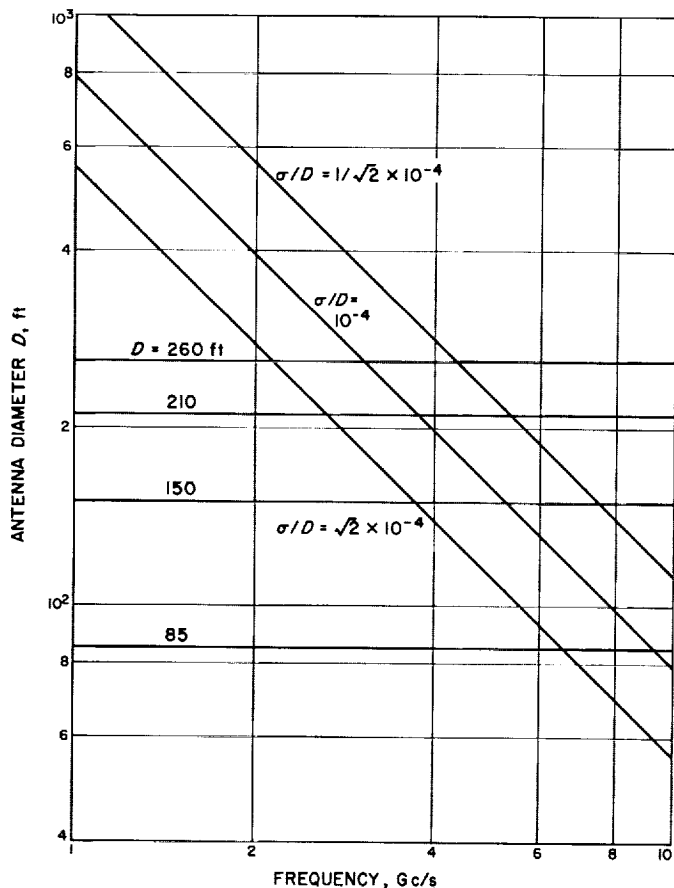**Fig. 2. Gain-limit antenna: Size vs frequency and σ/D**

B. The Propagation Medium

The propagation medium affects communications performance in two ways. First, atmospheric and cosmic sources contribute noise to the receiver; and second, atmospheric turbulence distorts the wavefront impinging on a ground antenna.

Figure 3 shows the system noise-temperature contribution due to the Earth's atmosphere and extra-atmospheric, or cosmic, sources (Ref. 3). Of particular interest is the fact that rain and, even, overcast have a
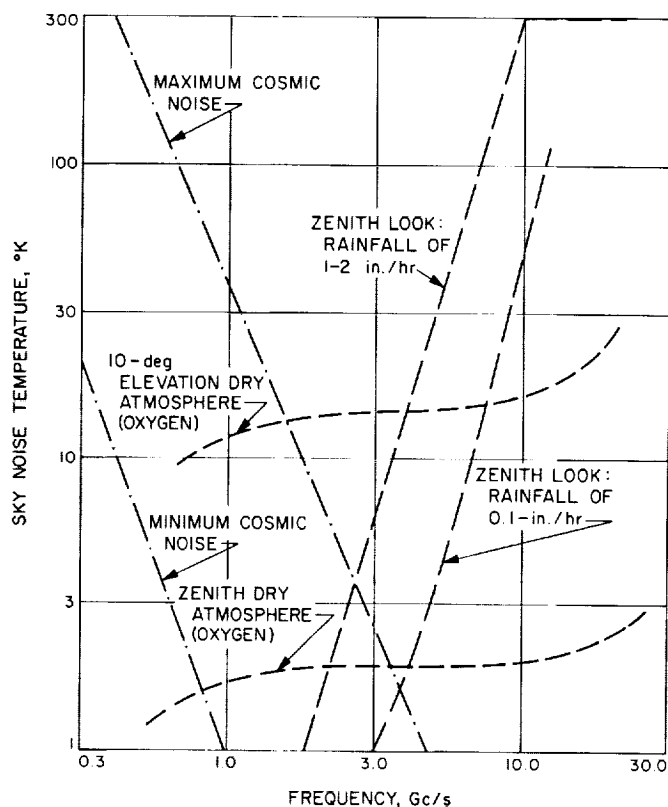

Fig. 3. Sky noise vs frequency

most serious effect on the performance above 2 to 3 Gc/s. For missions requiring ultra-high station reliability (e.g., impacters, planetary entry, and voice link), the possibility of a communication grey-out due to inclement weather cannot be tolerated. For this reason, in examining the frequency dependence, a condition of moderate rainfall will be assumed. Also, for the same reasons, maximum cosmic noise and minimum 10-deg elevation angle must be assumed. These choices are compatible with the established practice of worst-case design in communications system analysis; the resulting selected atmospheric/cosmic noise model is shown in Fig. 4, and the corresponding atmospheric attenuation model in Fig. 5.

The effect of the atmosphere in perturbing an incoming wavefront is depicted in Fig. 6, and is given quantitatively in Fig. 7 (Refs. 4, 5). It is interesting to note that this particular atmospheric effect is considerably worse at radio frequencies than at optical frequencies, due primarily to water vapor in the atmosphere, which has a severe effect at radio frequencies but a negligible effect at optical frequencies (Ref. 6). Attenuation due to aerosol particles—e.g., clouds—is markedly worst at optical frequencies, however. Within the broad spectrum of
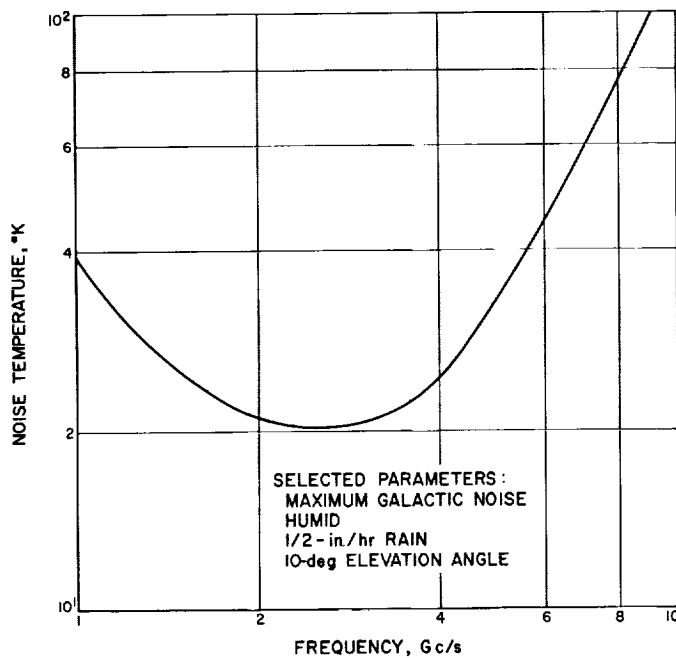
Fig. 4. Selected atmospheric/cosmic noise-temperature model

Fig. 5. Selected atmospheric attenuation model

radio frequencies, the σ due to turbulence is independent of frequency; the *effect* of this σ is more severe at higher frequencies.

C. Resultant Physical Distortions

The physical distortions in an antenna reflector due to mechanical deflections caused by gravity, wind, thermals, and panel effects and to manufacturing tolerance may be determined by a realistic scaling of data from thoroughly investigated designs. A high-quality paraboloidal antenna, similar to the NASA/JPL 210-ft-diam Advanced Antenna System, operating at peak environmental conditions of 30-mph winds, sun-induced thermals, and 10-deg elevation angle, is selected as a good standard for comparison.

These data are combined in Fig. 8 with phase-front distortions due to atmospheric effects, showing their resultant effect, which is very nearly equal to a constant, $\sigma/D = 10^{-4}$, over the range of interest (see also Ref. 7). It is seen that, with the structural accuracy presently achievable, atmospheric turbulence presents no significant contribution to the resultant, except in the case of small antennas.

The surprising result presented here, that tropospheric turbulence is a problem for small antenna apertures but

proposes no problem for large apertures, is due to putting this effect in the proper framework of perturbation divided by diameter, rather than perturbation, per se. In this correct framework, the atmosphere effect may be treated, as it should be, in the same manner as reflector-surface tolerance.

This result is also applicable to arrays in which each array element separately phase tracks the incoming signal (the *adaptive phasing technique*). If adaptive phasing were not used, large-scale wavefront distortion would cause phasing errors proportional to the overall array dimension, rather than the dimension of a single element. To employ adaptive phasing does, however, require that the signal received on each array element be above threshold for that element alone. This requirement can, under some circumstances, impose a penalty in the form of increased spacecraft power.

σ = CONSTANT $\times D$
σ/D = CONSTANT

a. MODEL OF LARGE-SCALE
WAVEFRONT DISTORTION

σ = CONSTANT
σ/D = CONSTANT $\times D^{-1}$

b. MODEL OF SMALL-SCALE
WAVEFRONT DISTORTION

$\sigma/D \approx$ CONSTANT $\times D^{-\beta}$
WHERE $0 \le \beta \le 1$

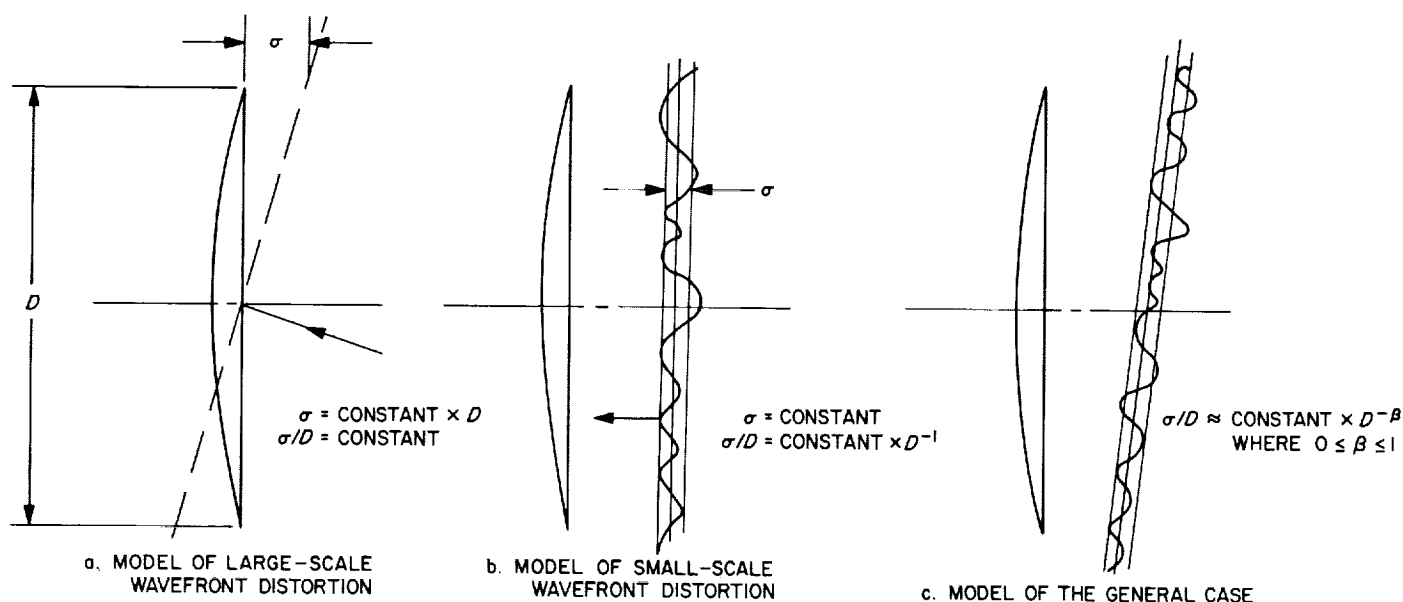c. MODEL OF THE GENERAL CASE

Fig. 6. Models of tropospheric wavefront distortion

D. Frequency Dependence of Communications Links

A convenient form of the basic communication equation is shown in Table 2. The final frequency dependence of a communication link is a resultant of the frequency dependence of the gain of the transmitting and receiving antennas, the frequency dependence of the receiver noise temperature, and the explicit f^2 term. It is generally known that technical or practical considerations may limit, or constrain, the gain which may be realized in either or both of the communication link antennas. Although contrary to intuition, there are situations in which frequency and data rate are inversely related; this is basically a result of the fact that, for a fixed gain, antenna frequency of operation and capture area are inversely related.

In this Report, it will be shown that the ground antenna will inevitably be gain-constrained; for the case of a single antenna, the gain will be constrained by the physical distortions discussed in the preceding section; for the case of the array, gain will be constrained by practical array-size considerations. The vehicle antenna may or may not be gain-constrained; it is generally felt that the gain-constrained vehicle antenna case will become increasingly important in the future.

A detailed consideration of the spacecraft antenna is essential to establishment of communication-link frequency dependence. There are three distinct cases for spacecraft antennas: (1) the omnidirectional antenna typically used on spacecraft for Earth-to-space command and, in some instances, for space-to-Earth telemetry; (2) the area-constrained high-gain antenna used for space-to-Earth telemetry, where the primary constraint is a limit on the physical size of the antenna due to booster shroud size and packaging and/or weight; and (3) the gain-constrained high-gain antenna where the primary constraint is a limit on gain due to attitude control and/or reliability and mission considerations. The third case is important, and it may arise in several different situations. As gain increases, the beamwidth of the antenna decreases proportionally, and the antenna must be pointed more accurately. Figure 9 illustrates this problem. If space-erectable antennas become practical, or as shroud sizes increase, pointing becomes the limiting factor. Pointing is primarily limited by spacecraft attitude-control limitations, spacecraft reliability, and complexity.

In some cases, a more nearly optimum spacecraft design is achieved by not having a movable spacecraft antenna at all. Eliminating the required servos, etc., and relaxing the attitude-control requirement saves considerable weight and increases reliability. The recent NASA/JPL *Mariner IV* is an example of this design (Ref. 8). In this case, the beam was broad enough in the ecliptic plane to provide good reception as the Earth angle changed during the mission. This non-tracking configuration limited the gain of the antenna.
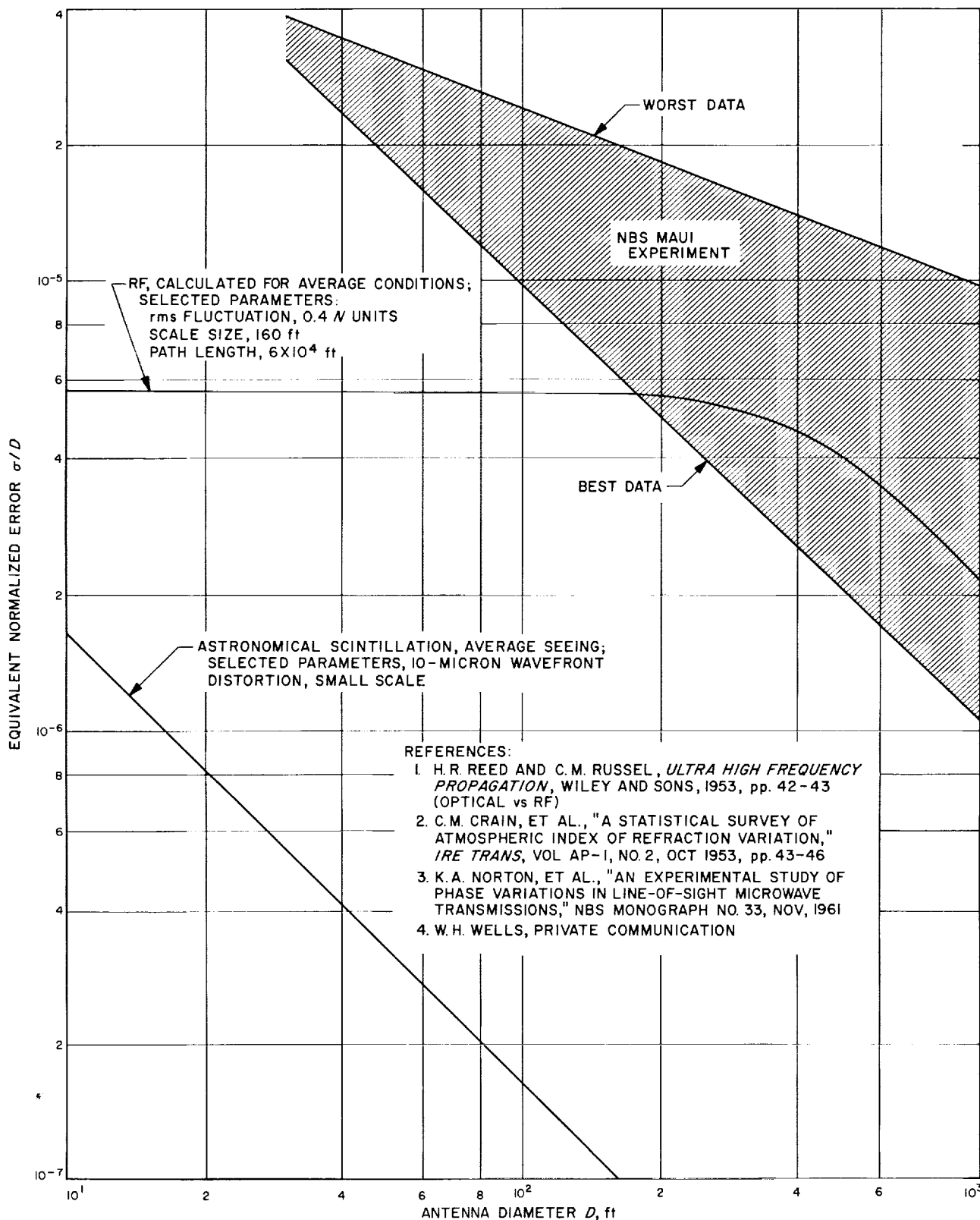
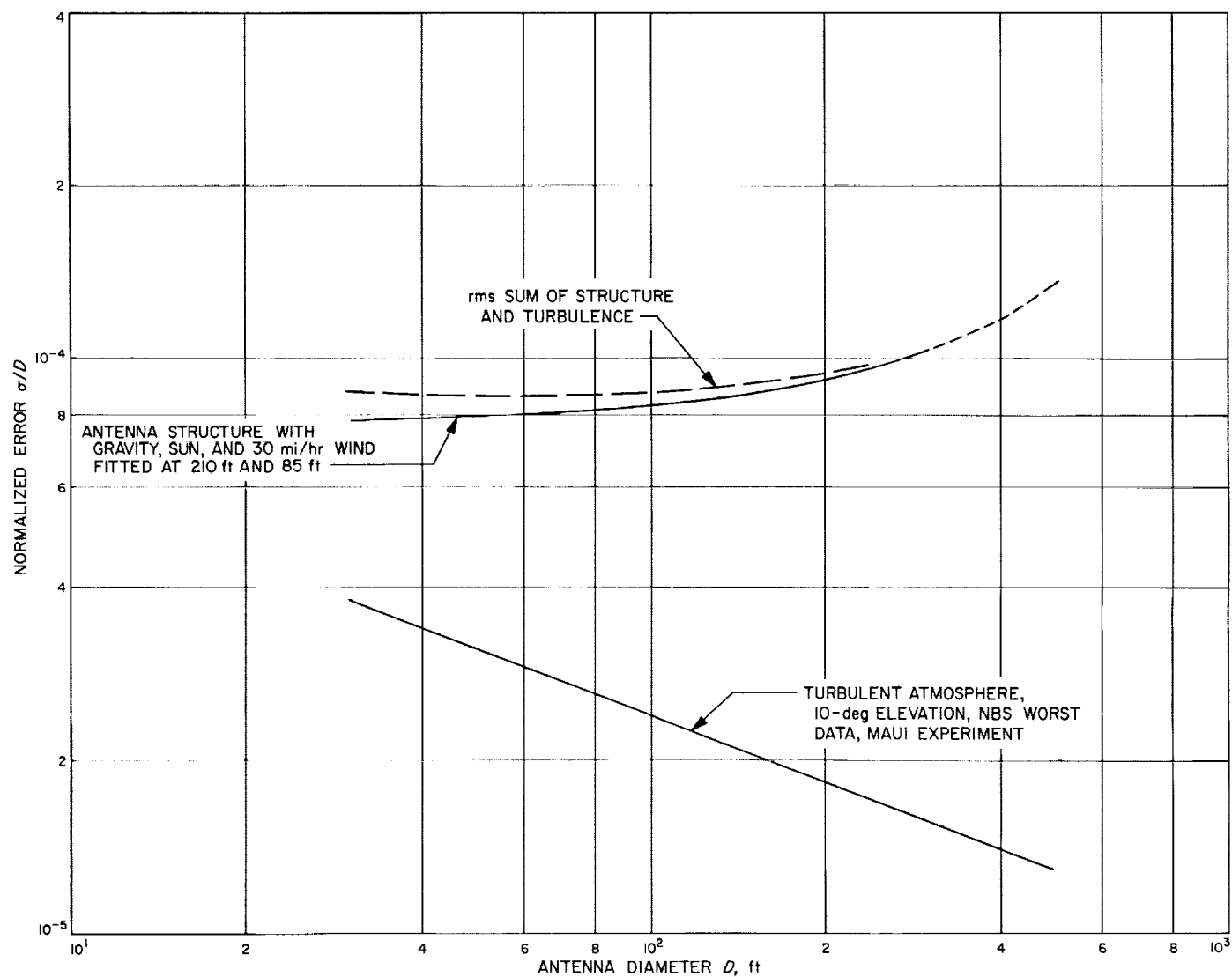Fig. 7. σ/D equivalent of the troposphere, 10-deg elevation angle

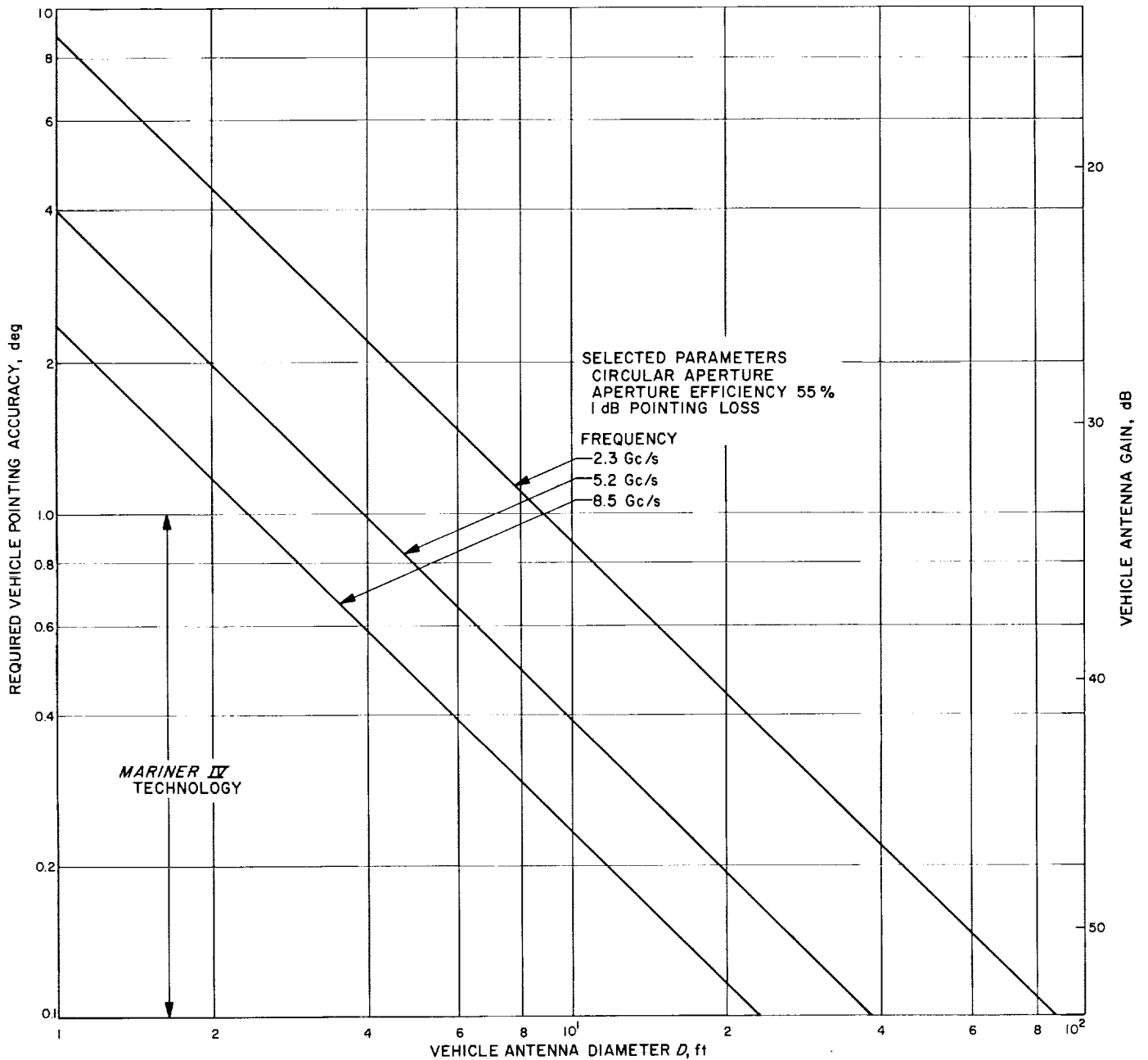**Fig. 8.** σ/D **vs** D **for structure and severe turbulence**

Fig. 9. Required vehicle-pointing accuracy vs diameter of vehicle antenna

The gain of the spacecraft antenna is, in effect, independent of frequency in the first and third cases above; each of these will be identified in this Report as the *gain-constrained* case. Spacecraft antennas can generally be built with the same order of σ/D as ground antennas and, being much smaller, will be operating well below their gain limit. Therefore, the gain of the spacecraft antenna is proportional to f^2 in the second case, which will be identified as the *area-constrained* case. When both ground system noise environment and physical errors are taken into consideration, resultant curves of overall system performance vs frequency for a single ground antenna are obtained as shown in Figs. 10 and 11 for the area-constrained and gain-constrained links, respectively. The envelope shown in these Figures represents the effects of antenna-noise contribution and of physical errors. Since Fig. 11 assumes a space-to-Earth link, the envelope in this Figure would be slightly different for the Earth-to-space omnidirectional command link, due to the different system effect of atmospheric absorption vs atmospheric noise. This difference will not appreciably alter the conclusions drawn from these curves due to the predominant effect of the $1/f^2$ variation.

Figure 10 shows that maximum performance is obtained at, or slightly below, the gain-limit point for the area-constrained link; the optimum frequency of operation is in the range of 0.7 to 1.0 × gain-limit frequency. Figure 11 shows that maximum performance is maintained up to a point of 0.5 to 0.7 × gain-limit frequency.

There are two other facts that tend to discriminate against operating too closely to the gain-limit frequency: (1) experimental data on the performance of antennas at gain limit are sparse, (2) performance becomes very sensitive to preconstruction estimates of σ/D, as illustrated in Fig. 1. A good choice of operating frequency is in the range of 0.6 to 0.7 × gain-limit frequency. At this point, or at any constant fraction of the gain-limit point, two relations stated earlier still hold: the gain at this point is inversely proportional to $(\sigma/D)^2$, and for σ/D = constant, antenna diameter and frequency are inversely proportional. With this choice of operating frequency, and for σ/D = constant, communication capability for a transparent atmosphere would be independent of the frequency/diameter choice in the area-constrained case, and inversely proportional to frequency-squared in the gain-constrained case. Atmospheric noise, however, seriously reduces performance above roughly 5 Gc/s, and extra-atmospheric effects strongly affect performance below 1 Gc/s.
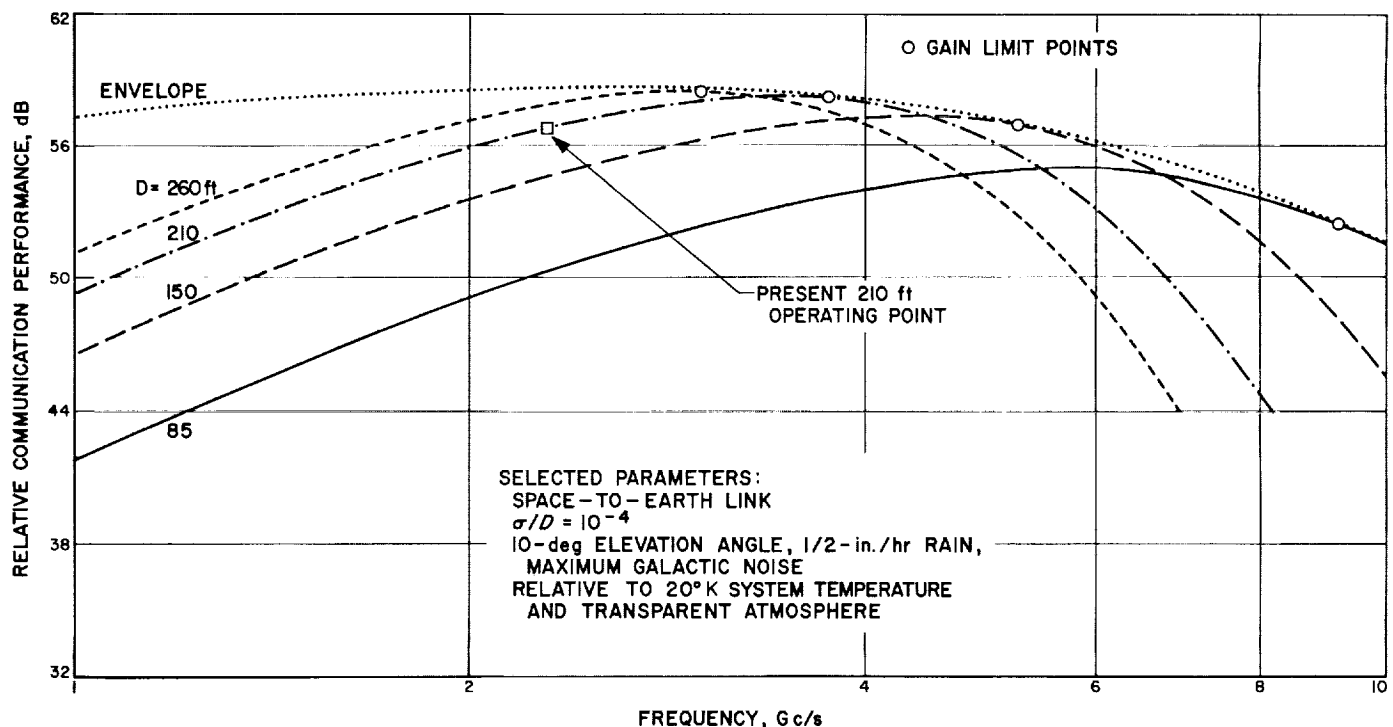

Fig. 10. Relative communication performance vs frequency and size for a single antenna, area-constrained link
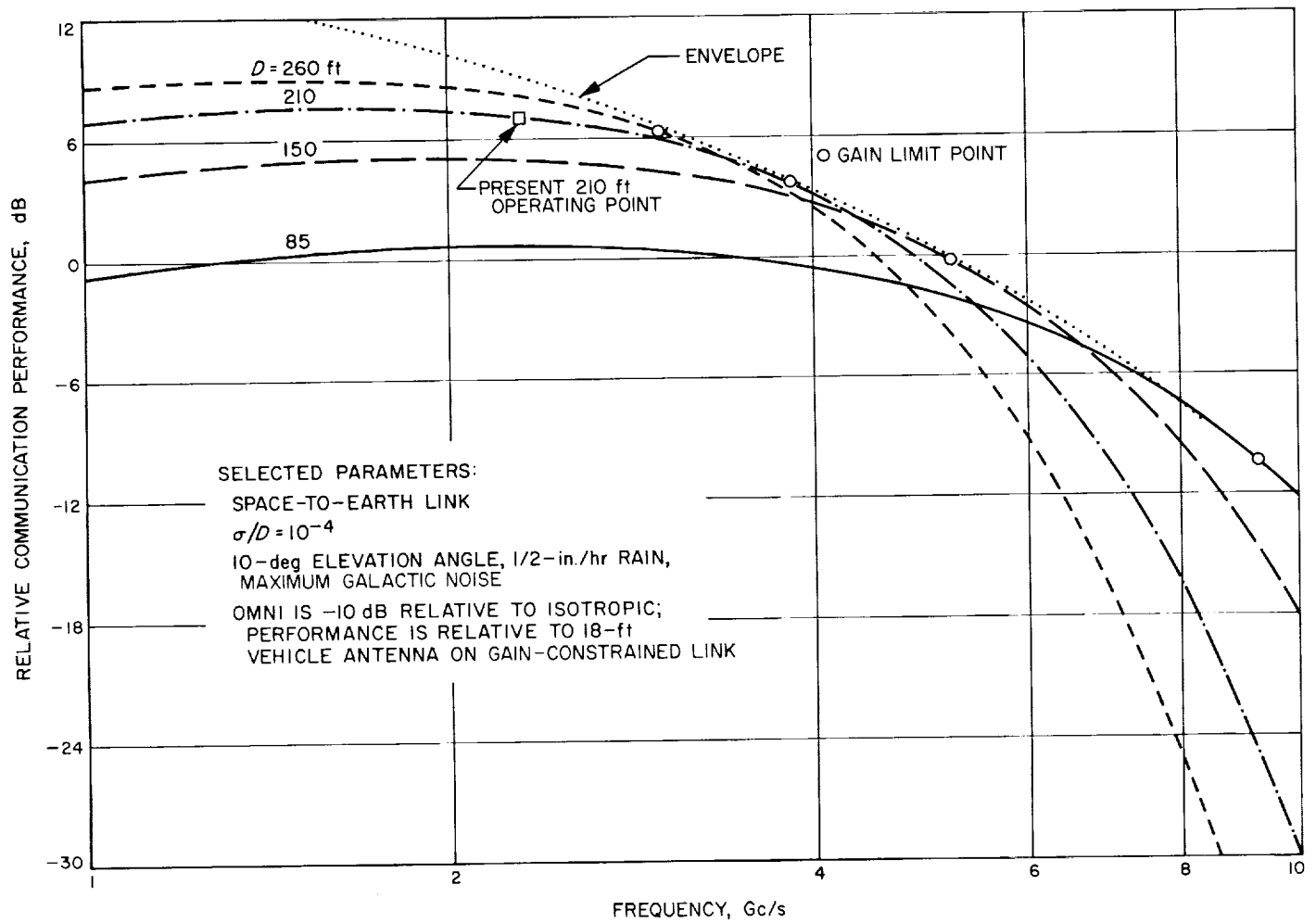
Fig. 11. Relative communication performance vs frequency and size for a single antenna, gain-constrained link

III. SINGLE ANTENNAS AND ARRAYS

A. The Effect of Antenna Size and Quantity on Communications Performance

Since antenna diameter and frequency are inversely proportional at the (performance) optimum frequency of operation, it follows from the previous section that for σ/D = constant (again neglecting the atmosphere for a moment), communication performance is independent of antenna diameter in the area-constrained case, and directly proportional to diameter-squared in the gain-constrained case. In both cases, performance is directly proportional to the number of antennas. Stating this another way, when operating at the point of optimum performance, in the area-constrained case, performance is primarily determined by the number of antennas; and in the gain-constrained case, performance is primarily determined by the total square feet of aperture. An important qualification is the fairly severe loss due to atmospheric noise at high frequencies; this loss strongly discriminates against operating frequencies corresponding to antennas smaller than 150-ft diam, as seen in Fig. 10. An important qualification to the second statement concerns the command use of the gain-constrained link.

It has been tacitly assumed in the above discussion that adaptive techniques would be used in an array. In order to realize an improvement in downlink communication performance with an array, the signals from each element must be added coherently. Due to uncertainties in the absolute location of the phase centers of the elements (arising from surveying error and various physical distortions) and because of large-scale wavefront distortion, adaptive techniques constitute the only method of achieving this coherency (Refs. 9–11). However, in the command case the only way of using adaptive phasing would be through an externally generated reference signal, perhaps from the spacecraft. Reliance on such a signal would seriously degrade the reliability of the command link. If coherency could be achieved, one 100 kW transmitter on each of two elements would be as effective as one 400 kW transmitter on a single element. But one 400 kW transmitter would cost roughly the same as two 100 kW transmitters, and would avoid difficult problems of information phasing, as well as possible fade-out due to destructive interference. For the foreseeable future, one large transmitter appears to be the best solution. In the command case then, performance is proportional to the square feet of aperture of a single element. Since command capability is relatively easily increased by increasing transmitter power, this case should be weighted less than the other cases.

The problem of determining optimum antenna size and number of antennas involves the following steps: (1) determining optimum size and quantity to maximize square feet per dollar for the gain-constrained case, excepting the command case; (2) determining optimum size and quantity for the area-constrained case by balancing the reduced cost of smaller antennas against the increased loss that is due to atmospheric noise at the corresponding higher frequencies; and (3) reconciling the somewhat conflicting requirements of steps 1 and 2 with the requirement of maximum element size for the command case.

B. Ground Station Cost as a Function of Antenna Size and Quantity

In performing the required economic study, a conceptual model of the station must be chosen. It is not critical that this model exactly correspond to the way such a station would be implemented 10 to 15 yr from now. Rather it is important that (1) a model be established from which conclusions can be drawn and (2) the sensitivity of the conclusions to model parameters be understood. Obviously, the solution actually chosen will be heavily weighted in the direction of minimizing sensitivity and the associated economic risks. This consideration weighs heavily, for example (as will be seen shortly) against use of small (100-ft diam, or less) array elements.

The conceptual multi-aperture station model consists of a master facility with buildings, antenna, and electronics; a number $(n-1)$, of slave facilities, antennas and electronics, and finally, the operations personnel, spares, etc. The cost has been established as a function of n, D (antenna element diameter), and years of operation. Three types of cost are assumed: (1) fixed costs, independent of n or years of operation; (2) equipment and facility costs which are a function of n; and (3) operations costs which are proportional to the years of operation and to n. For the second category, the unit cost is assumed to be reduced by a *learning curve* factor of 0.95 each time the quantity n is doubled. This factor is used for electronics, facilities and antennas. The antenna cost is taken as a power law fit to an 85-ft antenna
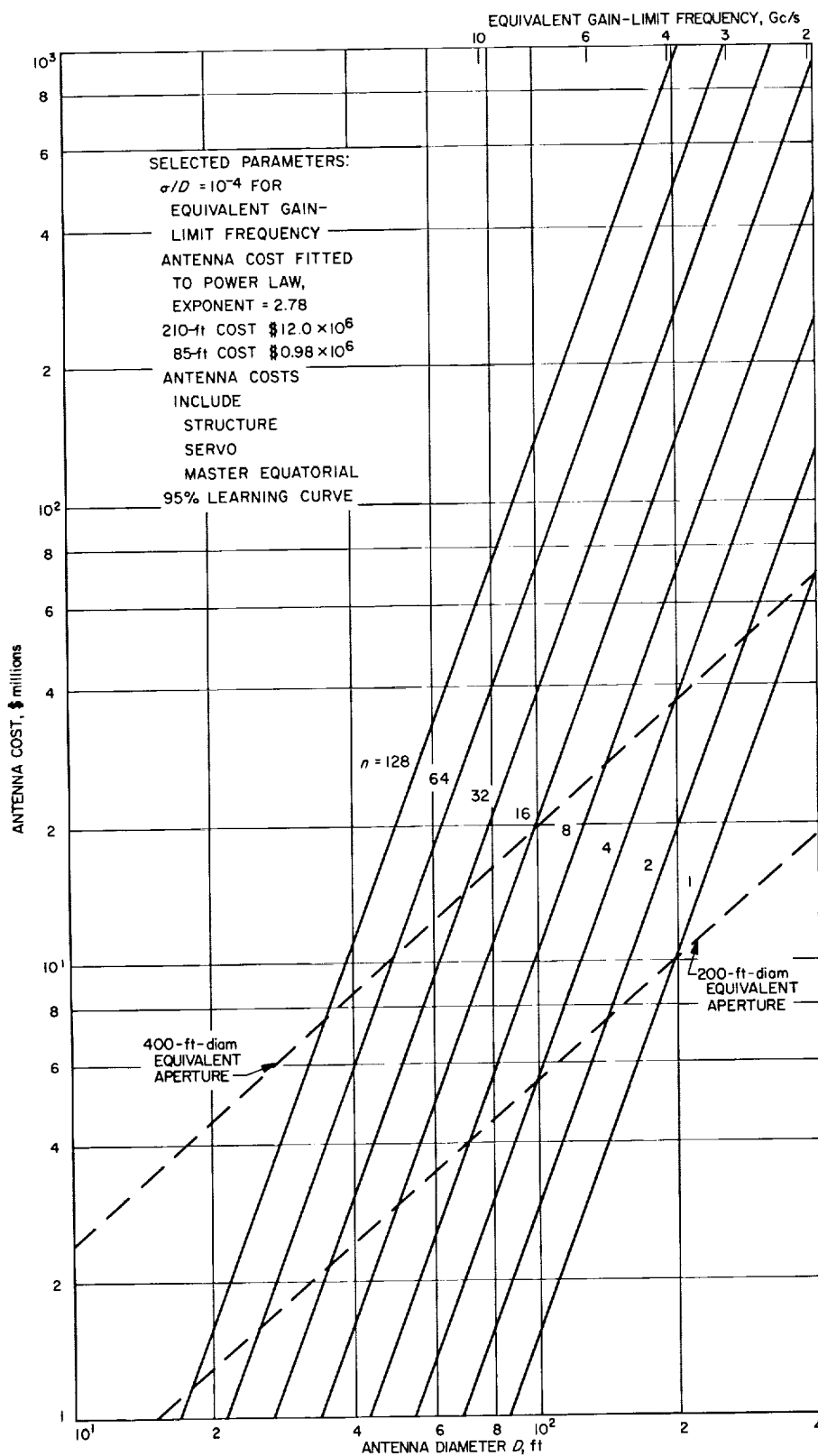
Fig. 12. Antenna cost vs diameter and number of units *n*

cost of $1 million and a 210-ft antenna cost of $12 million. Land costs are not considered.

Two sets of electronics, facilities, and operations costs are used in this Report: the nominal case, which is based on actual costs of equipment and operations as they appear in various NASA/JPL Deep Space Network internal reports; and a minimal case, which is deliberately estimated as being well below any costs experienced in any operational network. These costs are shown in Fig. 12 and Table 3. It should be emphasized that minimal costs are to be used primarily for testing sensitivity of results to assumed costs, rather than representing reality. They do, however, provide a better test than a maximum cost case, in that the minimal case will favor an array of smaller antennas, known to be a serious competitor of single large-aperture paraboloids. The equation for total station cost is given in Table 4.

Due to the very large investment in the ground station, it must be planned for use over a long time period in order to be amortized against a significant number of spaceflight operations. On the other hand, this period is limited by technological obsolescence and by the predictability of space program support in the United States and in the countries where the *Deep Space Network* stations are located. Consideration of these factors leads to a planned lifetime of 10 to 15 yr.

C. Maximum Square Feet of Aperture for a Fixed Cost

In any ground antenna array, if the element diameter is too small, the array will be too expensive, because of the electronics and operations costs for the large number of elements required; if the element diameter is too large, the array will be too expensive, due to the structures cost. For a required total aperture area, if we differentiate the equation given in Table 4 with respect to the number of antennas, n, we can determine whether costs increase or decrease as n is increased. It is found that this slope is always positive (increasing costs with increasing n) at $n = 1$ until a certain minimum total area is required. This crossover point occurs at an area equivalent to an antenna of diameter ranging from 162 ft, for a 10-yr writeoff with minimal costing, to 264 ft, for a 15-yr writeoff with nominal costing. Therefore (neglecting other cases for the moment), for total apertures less than or equal to the aperture of an antenna roughly 150 to 250 ft in diameter, a single antenna should be

Table 3. Selected costs

Item	Master cost		Slave cost[a]	
	Nominal	Minimal	Nominal	Minimal
Facilities	2.5×10^6	2.5×10^6	0.24×10^6	0.12×10^6
Electronics	3.1×10^6	2.5×10^6	1.80×10^6	0.51×10^6
Operations	2.6×10^6/yr	2.6×10^6/yr	0.61×10^6/yr	0.22×10^6/yr

[a]Add a fixed array-controller cost of 0.5×10^6 for $n > 2$. A learning curve of 0.95 is applicable to the first slave and every doubling of the total number of antennas thereafter. (Applies to facilities and electronics.)

Table 4. Station costs

Resultant	Computation
STATION COST C =	(Cost of n antennas of Diam $D = n \times 0.95^{\log_2 n} \times 4.37D^{2.75}$)
	+ (Cost of master electronics and facilities)
	+ (Years) $\times$ (Cost of master operations)
	+ $(n - 1) 0.95^{\log_2 n} \times$ (Cost of slave electronics and facilities)
	+ (Years) $\times$ $(n - 1) \times$ (Cost of slave operations)

used. For total apertures exceeding this by an appreciable amount, two or more antennas should be used.

Figure 13 shows total costs for a 10-yr period vs antenna size for apertures equivalent to a 500-ft and a 700-ft-diam paraboloid. Figure 14 shows total cost for a 15-yr period. Several important facts are illustrated by these two Figures: (1) Optimum antenna size is not very sensitive to whether the writeoff period is 10 or 15 yr, or to the total aperture area. (2) Optimum antenna size varies from slightly over 150-ft diam to slightly over 250-ft diam between the minimal and nominal costing. (Had maximum electronics and operations costs been used, the diameter would have been greater than 250 ft, assuming such antennas could be built.) Between the limits of 150 and 250 ft, total cost varies very little. In
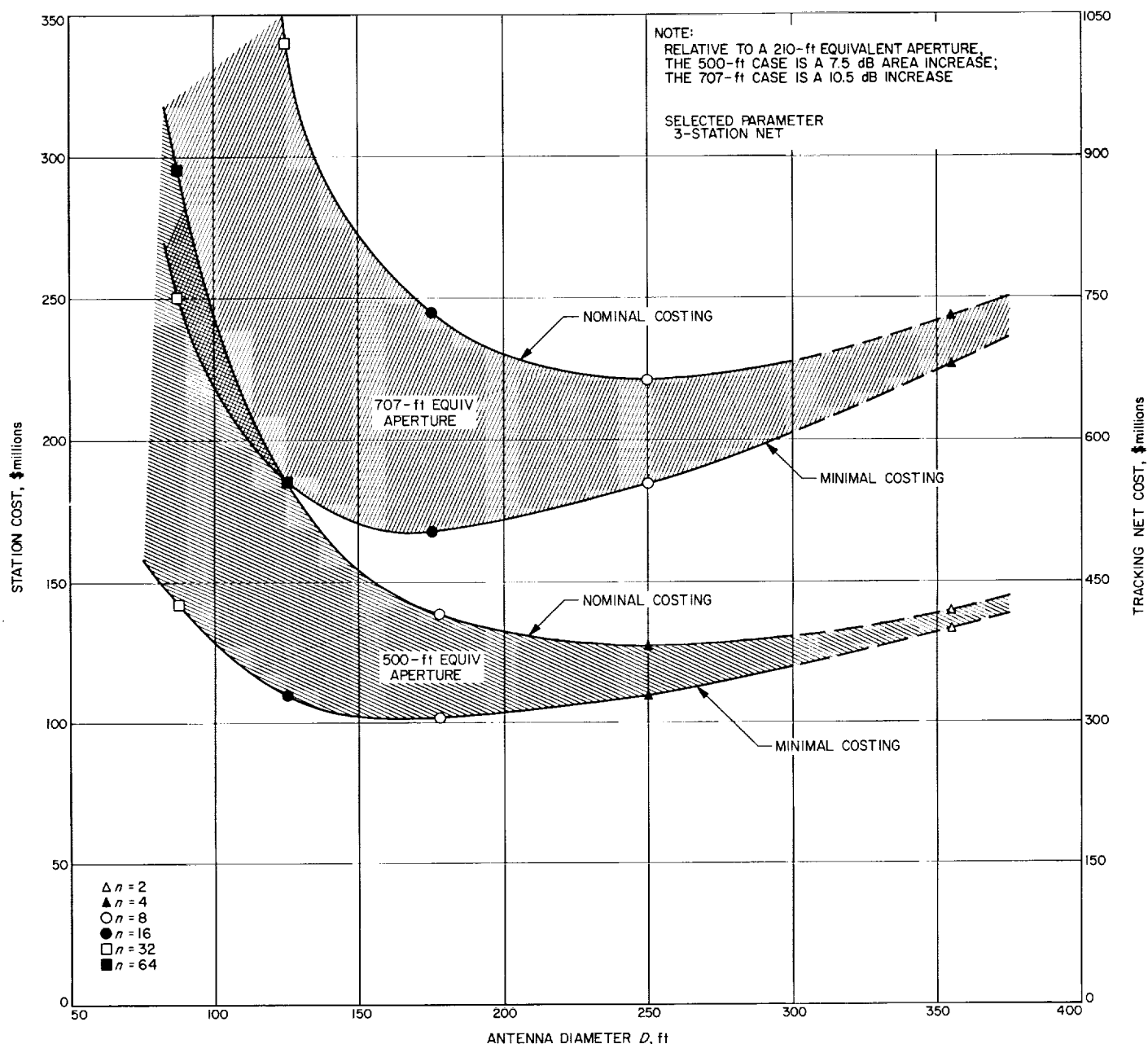

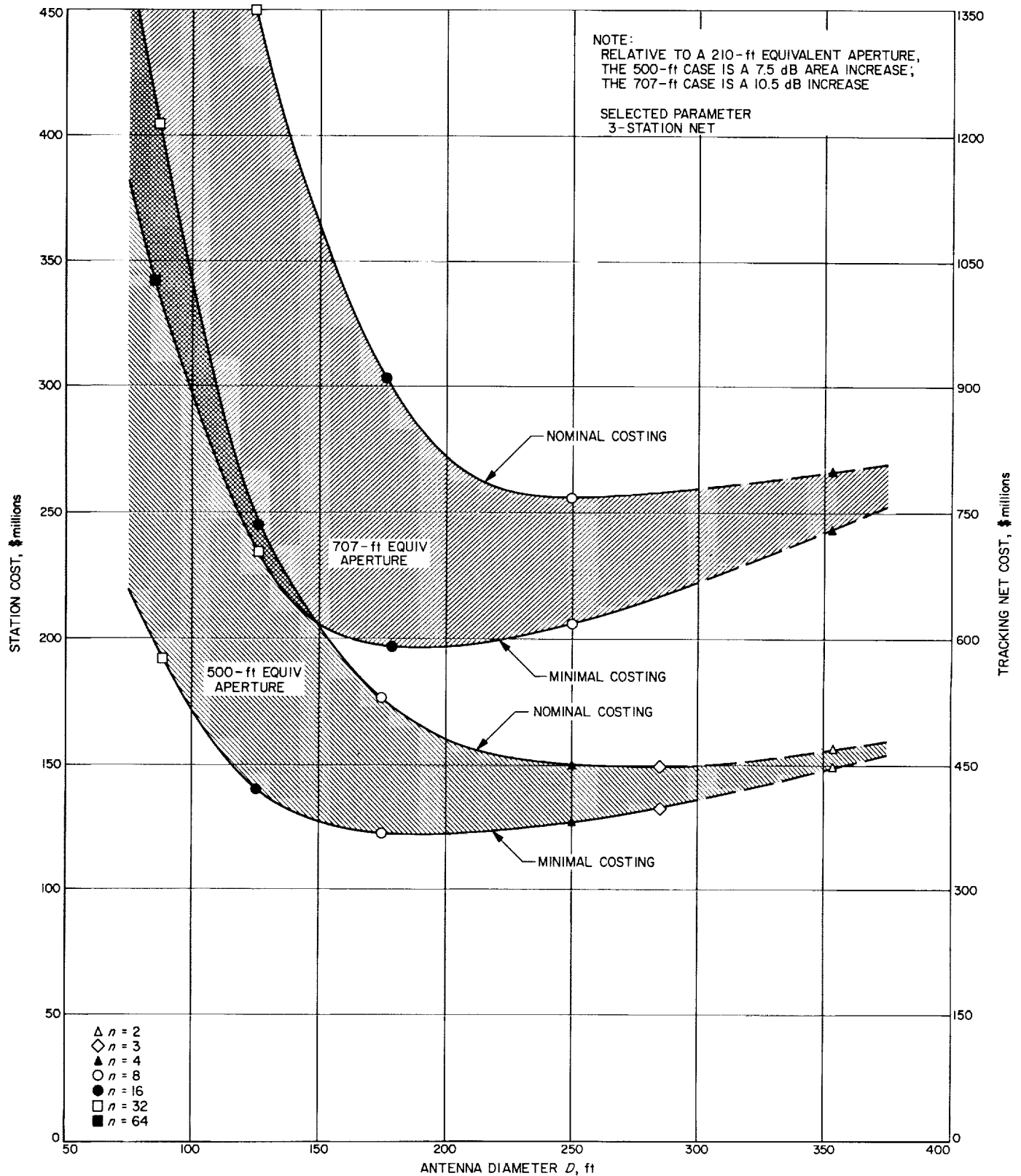**Fig. 13. Total cost vs antenna size for 10-yr operation**

Fig. 14. Total cost vs antenna size for 15-yr operation

fact, the total cost using 200-ft antennas is within 7% of minimum cost for the case least favorable to that diameter. (3) The sensitivity of total cost to costing assumptions becomes greater as antenna size is decreased. For example, total cost for a six-element 200-ft antenna array increases roughly 30% as assumed costs go from minimal to nominal; total cost for the equivalent 25-element array (100-ft-diam antenna) increases almost 100% as assumed costs go from minimal to nominal. In other words, a miss-estimate on the low side of electronics and operations costs can have much more drastic financial consequences if the element antenna diameter is too small rather than too big.

We have shown, then, that on a dollar-per-square-foot basis (the proper criteria for the gain-constrained case): (1) for total aperture area less than or equal to the area of a 200-ft-diam class paraboloid, a single antenna is cost optimum, and (2) for larger total aperture areas, an array should be used, but the optimum element size is still in the 200-ft-diam class.

D. Maximum Performance for a Fixed Cost

With the same costing formula given in Table 4, the question of optimum design may be approached somewhat differently. The various options that could be obtained for a fixed amount of money may be considered, and the resulting performance of different cases compared. It is found, for example, that 2.3 85-ft antennas[1] cost as much as one 210-ft antenna over a 15-yr period. The relative performance of these two cases is illustrated along with several other options in Figs. 15 and 16 for gain-constrained and area-constrained cases, respectively. These Figures also illustrate the resultant frequency dependence of the system.

The previous conclusion that antennas in the 150- to 250-ft-diam class are cost optimum for the gain-constrained link is confirmed by Fig. 15. In addition, it

---

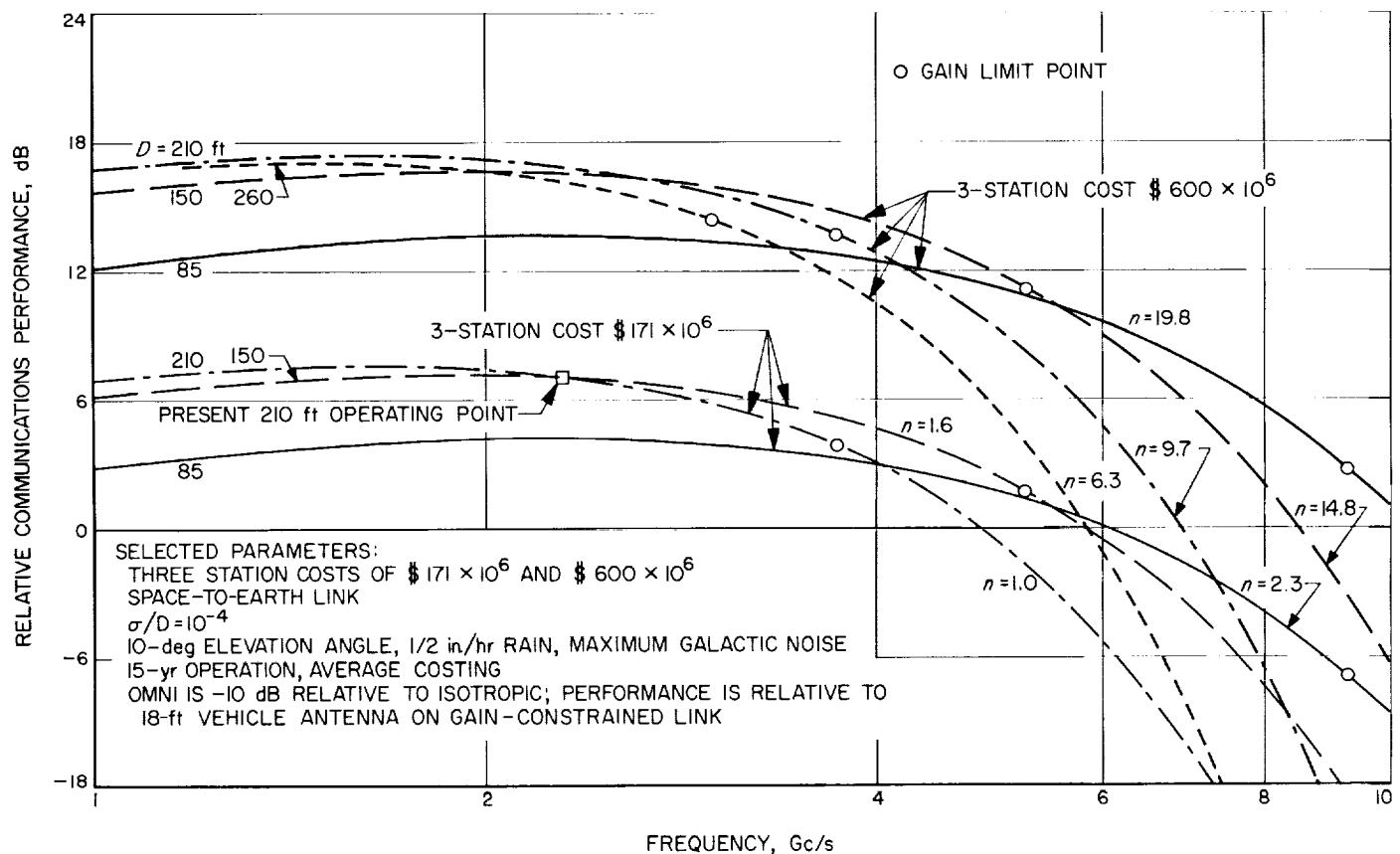[1]Fractional antennas are used throughout the Report for reason of mathematical convenience.

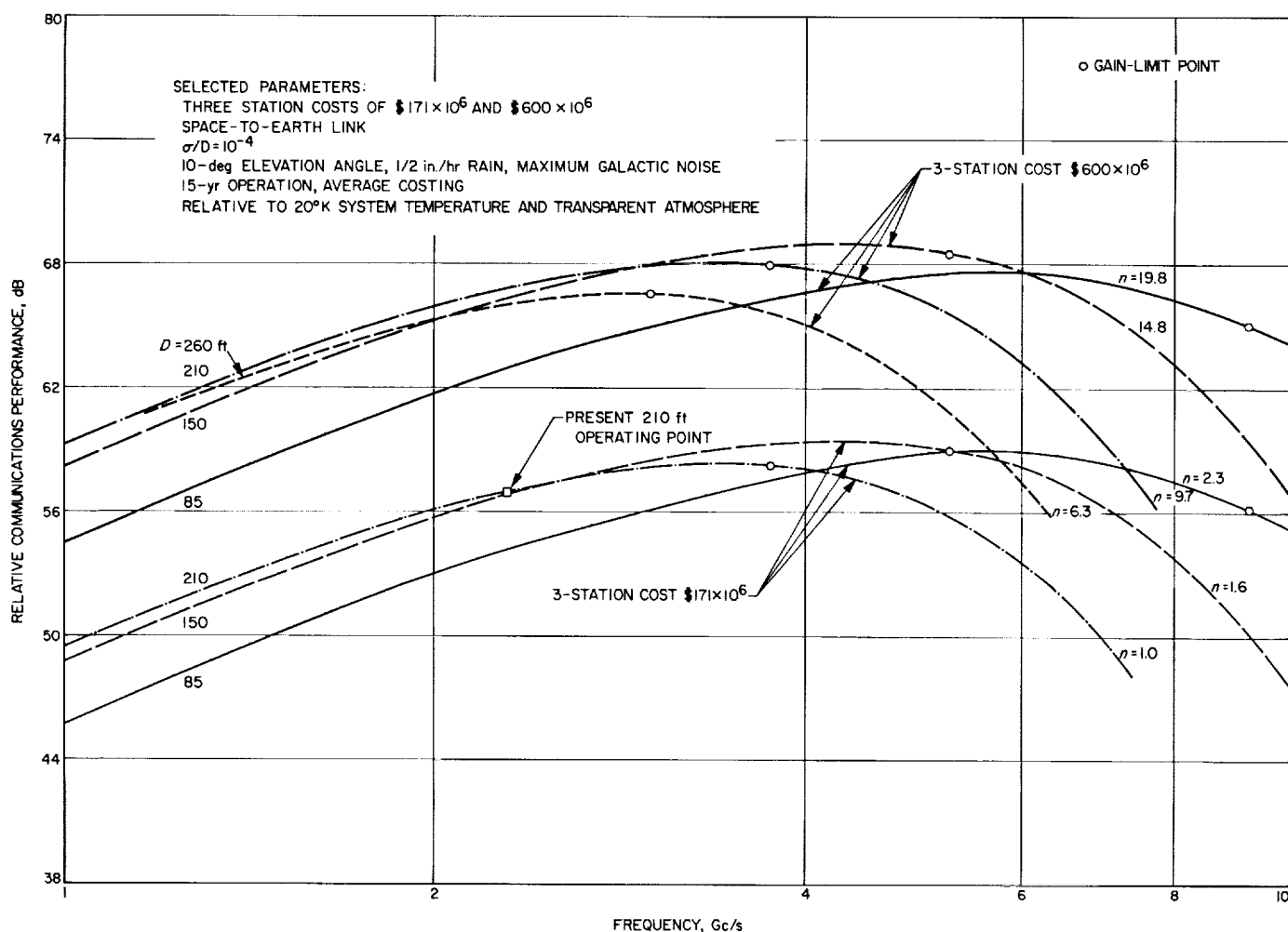Fig. 15. Fixed cost array performance vs frequency, gain-constrained link

Fig. 16. Fixed cost array performance vs frequency, area-constrained link

is seen that the optimum frequency of operation is in the 1 to 3 Gc/s range.

From Fig. 16 it is clear that antennas in the 85- to 210-ft class are cost optimum for the area-constrained link, and that the optimum frequency of operation is in the 2 to 8 Gc/s range.

These Figures also show that within the ranges of frequency and antenna size just stated, performance is relatively insensitive to the particular frequency/diameter choice. This result naturally leads to consideration of other factors that may influence the decision. One obvious factor is that higher frequencies and the associated smaller antennas require more antennas, with all the attendant technical and logistic problems. Another factor, as was pointed out earlier, is the increased sensitivity

to costing assumptions of the smaller antennas. A final consideration that is applicable to the space-to-Earth link is the spacecraft acquisition problem. All presently known operationally reasonable acquisition methods require that a single element of an array be capable of achieving phase lock on the spacecraft signal (Refs. 9–11). These several considerations discriminate against small element sizes.

For these reasons, in addition to the criteria for the command link, the best choice of antenna diameter is the largest antenna in the range of acceptable values in the area-constrained case; a choice that falls roughly in the middle of the acceptable values in the gain-constrained case. A 210-ft-diam antenna (or an array of these antennas for still larger apertures) operating at from 2 to 2.5 Gc/s satisfies this specification.

IV. GROUND STATION DEVELOPMENT VS SPACECRAFT DEVELOPMENT

A. Cost of Increased Ground Station Communications Capability

A cost-optimum ground station antenna configuration has been established, with estimates of cost vs performance. Figures 15 and 16 show that to increase performance by a factor of approximately ten over the planned Deep Space Instrumentation Facility (DSIF) 210-ft-antenna capability (which is a factor of 60 over the 85-ft-diam antenna network) for either the gain-constrained or area-constrained case, would cost, roughly, $400 million. This is clearly very expensive. In comparison, the factor-of-six increase obtained by going from 85-ft antennas to 210-ft antennas represented a difference in cost of $33 million. This order-of-magnitude change is due to two facts: (1) At the 85-ft level the antenna was a small fraction of the total cost and, therefore, a larger antenna did not affect total cost dramatically. (2) Grossly speaking, in the range of very large equivalent apertures, doubling the performance means doubling the cost; as the installation becomes larger and the amount that is doubled becomes larger, the cost pyramids.

The current estimate on the cost of a single 400-kW transmitter installation is between $1- and $2 million. A 400-kW transmitter represents a forty-fold increase over the current 10-kW DSIF transmitters if used on 85-ft antennas and a 240-fold increase if used on the 210-ft antennas. Clearly, increased transmitter power is presently the best choice for increasing command capability, and it will remain the best choice for some time.

B. Cost of Increased Spacecraft Communications Capability

A detailed examination of spacecraft tradeoffs is beyond the scope of this Report. The intent of this Section is to obtain a reasonable estimate of the cost of spacecraft improvement, which will enable a comparison with ground station costs. Difficult questions of implementation and reliability tradeoffs will not be considered. Assuming a good spacecraft design, and in the absence of overriding constraints, the costs of increasing spacecraft performance by any of the available options should be roughly equal. We will consider the cost of increased transmitted power as representative. Increased power means increased weight; total increased cost is then the increased cost of the transmitter and power source, plus the cost of the increased weight.

Table 5. Mariner Mars weights and powers

Subsystem	Weight, lb	Power, W	Remarks
Science	65	39	
Power and Cabling	203	50	
Attitude control and propulsion	122	30	
Structures, actuators, etc.	92	—	
Communications, except transmitters	57	34	
Transmitters	11	39	10W radiated
Tape recorder	17	8	5×10^6 bits
Antennas	8	—	3-ft diam, fixed
Totals	575	200	

Table 5 shows weights and powers for the NASA/JPL *Mariner* Mars Mission (Ref. 12). Consider the possibility of increasing the radiated power from 10 W to 100 W. The weight of the transmitter would probably increase very little—perhaps 4 lb. For each additional radiated watt, approximately 4 W of raw power are needed. Figure 17 shows power vs weight for several existing and future powerplants (Ref. 13). The additional power source required would add 100 to 150 lb, and would cost approximately $0.4 million for the solar panels.[2] Figure 18 shows booster capability (Ref. 14) vs cost (Ref. 15). Interpolating between boosters, the cost for the increase in weight is approximately $1 million.[3] Development cost of 100-W transmitter is currently estimated as being, also, near $1 million. In the *Mariner* case, this development cost could be spread over three spacecraft. The difference in cost of the actual transmitter hardware is considered negligible. The result is an increased cost of roughly $1.7 million per spacecraft.

---

[2] Actually, the solar panel area was limited by packaging within the booster shroud as well as by weight in the *Mariner IV*.

[3] Also see Reference 16. This mathematical convenience is, of course, not real in practice. Instead, the next largest booster would be considered, a spacecraft designed, new power levels derived, and then the equivalent ground improvements costs calculated. On this basis, the 85-ft ground antennas are a match to the *Atlas* class boosters, 210-ft single antennas to *Saturns*, large (about 10 element) arrays of 210-ft antennas to *Nova* boosters or multiple-rendezvous *Saturns*.
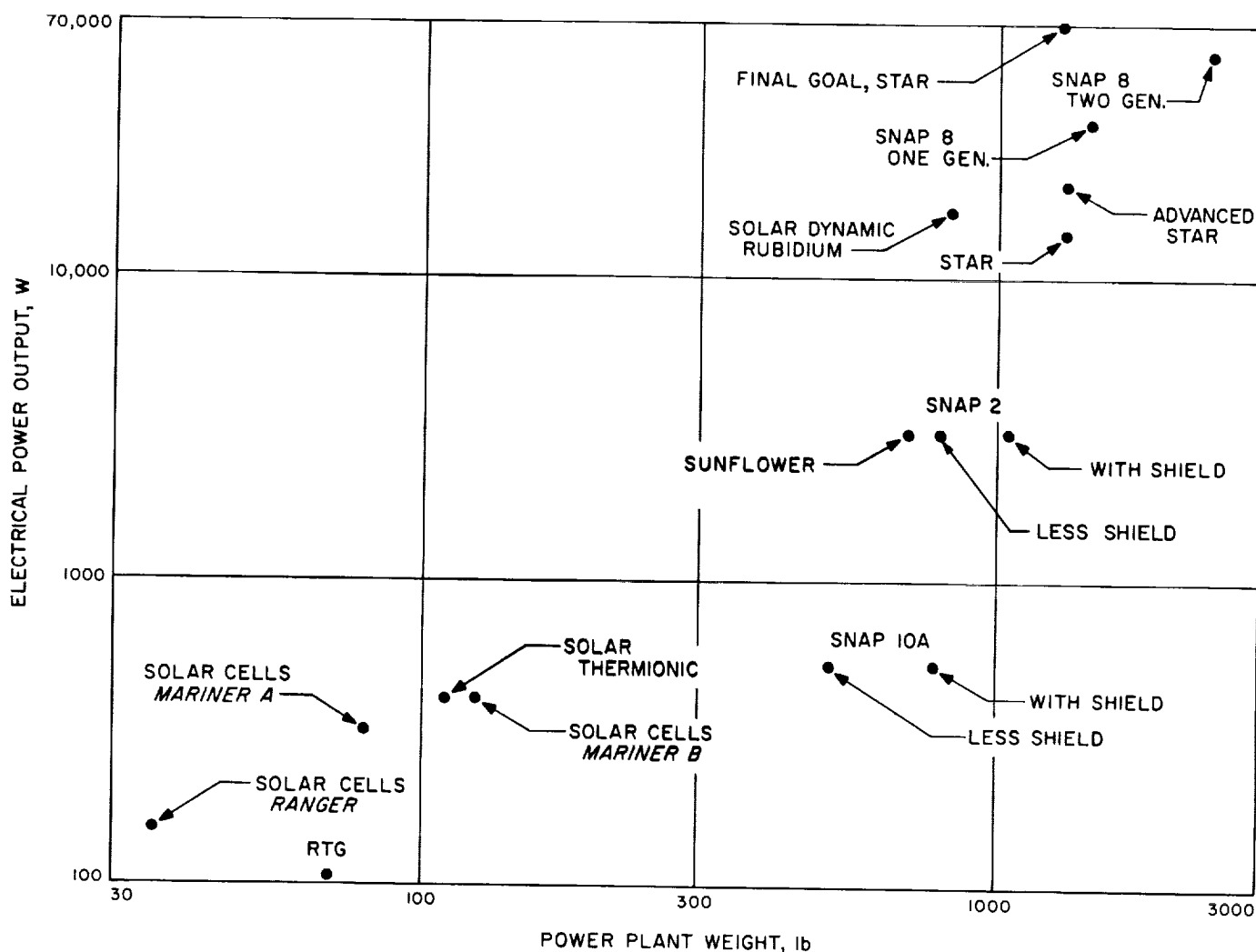
Fig. 17. Future spacecraft powerplants

A similar analysis based on a hypothetical future spacecraft in the 10,000-lb range using a nuclear power source and radiating 100 W to 1 kW of power, results in a cost of $5- to $7 million per spacecraft. This last number is necessarily approximate, but it does appear that increased transmitter performance at high ranges of power would not cost more than a factor of ten more than increased transmitter performance at relatively low ranges of performance.

If two spacecraft per year are constructed, on the average, over a 10- to 15-yr period, the cost of increasing communications performance by increasing the transmitter power on each of these spacecraft is roughly $30- to $50 million for the 10–100 W increase, and $100- to $200 million for the 100 W to 1 kW increase.

Comparison of these costs with the costs of improving ground station performance, indicates that the development of a 210-ft-diam antenna capability is economically compatible with the 10- to 100-W spacecraft power range and that a minimal array capability (i.e., 2 to 4 elements of 210-ft diameter) may be compatible with the 100-W to 1-kW power range.
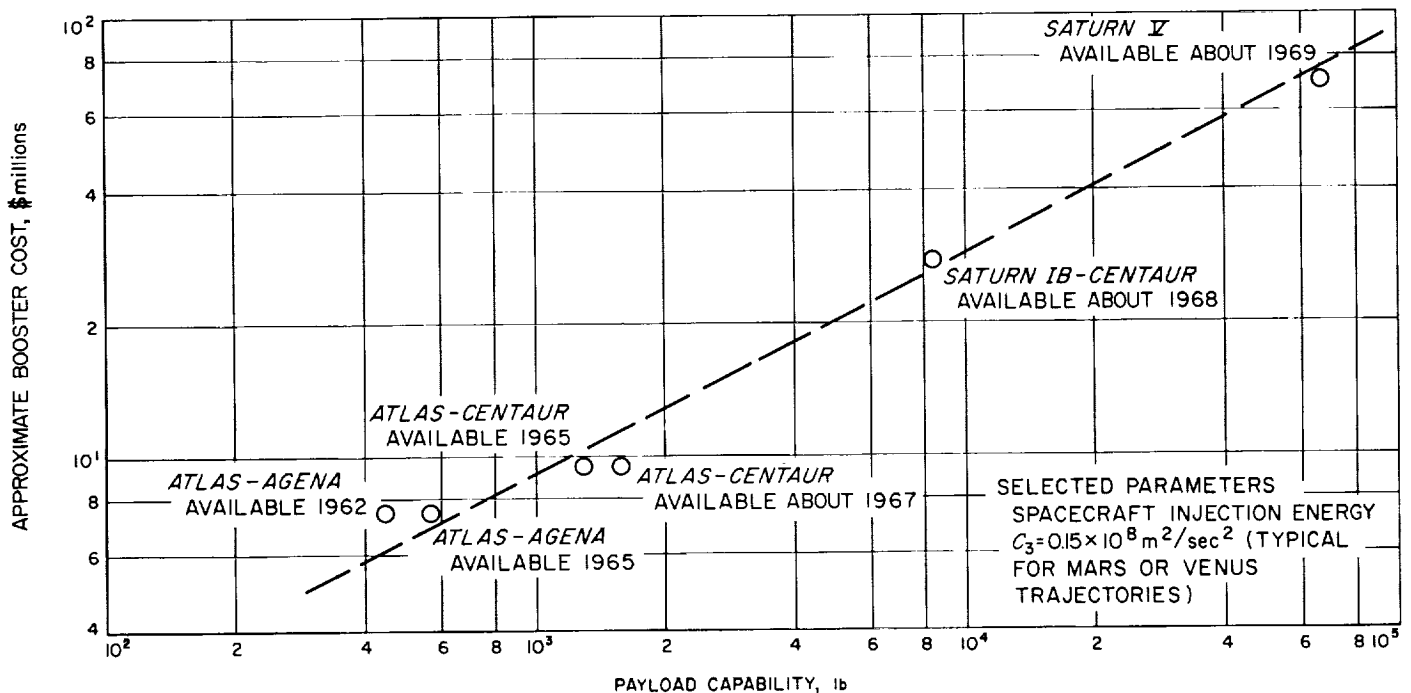
Fig. 18. NASA launch vehicle capability

V. SUMMARY AND CONCLUSIONS

Three questions have been considered in detail in this Report:

(1) How large a ground antenna aperture is justified when economically balanced against potential improvements in spacecraft performance?

(2) What is the best method of achieving this aperture—a single antenna, or an array of antennas?

(3) What is the optimum frequency of operation?

To answer these questions, the Report has concentrated on an economics analysis because there do not appear to be any serious technical problems which cannot be obviated by proper design of the ground station.

Costing data used in this report generally come from official NASA/JPL financial documents reporting actual expenditures and costs. Extrapolations, where necessary,

are based on past experience and are as realistic as possible. It is equally as important to test and understand the sensitivity of conclusions to selected values, as it is to seek the nominal values which are exactly correct. A more detailed study could be aimed at refining the cost figures, but it is very unlikely that the conclusions will change because no areas of great sensitivity have been found.

In answer to the first question above, it was shown in this Report that equivalent apertures, large compared with that of a 200-ft-diam class paraboloid, are very expensive and are probably not economically warranted for another 10 to 15 yr, at which time manned spacecraft may be under development for flights to the planets. It was further developed that a three-longitude network of 210-ft-diam antennas is economically compatible with 10- to 100-W transmitter level spacecraft boosted by *Saturn* class vehicles.

The characteristics and requirements for missions more than 10 to 15 yr from now are not in clear focus; a rough estimate involves *Saturn V* launch vehicles, 10,000-lb planetary spacecraft, nuclear reactor power sources, and a spacecraft radiated power level of perhaps 1,000 W. An economically compatible ground station network might involve small arrays (2 to 4 elements, 210-ft diam) at each of the three longitudes.

In answering the second question listed above, it has been tacitly assumed throughout the Report that the antenna type to be utilized was the fully steerable paraboloid. The relative merit of fully steerable paraboloids and non-steerable reflector-type ground antennas was reviewed in detail as a preliminary part of the AAS project; since that time, little has happened to affect the basic conclusion that steerable paraboloids are the best choice as the work-horse antenna type. For example, a fundamental problem exists with the fixed spherical-reflector approach; high aperture efficiency and wide-angle scan designs are mutually exclusive (Refs. 17, 18). The multiplate antenna recently tested by AFCRL also suffers from coverage problems (Ref. 19), compounded by high antenna noise temperature (Ref. 20). Both of these approaches appear to offer a large aperture at a low cost; however, when the factors mentioned above are taken into consideration, this apparent advantage rapidly diminishes. A final evaluation shows that when used in deep space communications applications, there is little or no economic gain over steerable paraboloids, which have the advantage of proven performance and well established costs.

The question of best antenna type thus reduces to one of ideal antenna diameter; it has been shown that an economic crossover point exists at approximately 200-ft-equivalent aperture, such that equivalent apertures in excess of this size are best realized by arrays of 200-ft antennas. Thus, a three-longitude network of 210-ft-diam antennas is a sound first step which is directly in line with possible future multiple aperture systems.

The original deep space communication frequency choice of 2.1 to 2.3 Gc/s for single antenna systems was made in 1961, largely on the basis of best performance (noise environment, see Fig. 4) and an assumption of ground station costs for a 210-ft antenna (since confirmed). In this study, it has also been shown that for *multiple-aperture economics optimization*, the 2.1 to 2.3 Gc/s and 200-ft-diam class antenna choice remains the best. It should be mentioned, however, that the external noise environment is favorable over a large band (2 to 6 Gc/s) and multiple aperture frequency optimization within this band involves the relationship between paraboloidal antenna size and reflector surface precision. Since this relationship is subject to change with technological progress in the structures field, it is possible that a higher frequency of operation, from 4 to 6 Gc/s, may become attractive at a future date. It has been shown in this Report, however, that such a change would improve only the information rate under special circumstances—namely, those in which the vehicle antenna is area-constrained, rather than gain-constrained by beam pointing considerations.

REFERENCES

1. Rechtin, E., Rule, B., Stevens, R., *Large Ground Antennas*, JPL Technical Report No. 32-213, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, March 1962.

2. Ruze, John, *Physical Limitations on Antennas*, TR No. 248, Research Laboratory of Electronics, MIT, ASTIA/AD 62351, October 1952.

3. Hogg, D. C., and Semplik, R. A., "Effect of Rain and Water Vapor on Sky Noise at Centimeter Wavelengths," *Bell System Technical Journal*, Vol. 40, pp. 1331–1348, September 1961.

REFERENCES (Cont'd)

4. Crain, C. M., et al., "A Statistical Survey of Atmospheric Index of Refraction Variation," *IRE Transactions*, Vol. AP-1, No. 2, pp. 43–46, October 1953.

5. Norton, K. A., et al., *An Experimental Study of Phase Variations in Line of Sight Microwave Transmissions*, NBS Monograph No. 33, National Bureau of Standards, Boulder, Colorado, November 1961.

6. Reed, H. R., and Russell, C. M., *Ultra High Frequency Propagation*, Wiley and Sons, New York, 1953, pp. 42–43.

7. "Technical Characteristics of Telecommunication Links Between Earth Stations and Spacecraft for Research Purposes," Report 218, *International Radio Consultative Committee, Documents of the Xth Plenary Assembly, Vol. IV*, International Telecommunication Union, Geneva, 1963, pp. 272–287.

8. Mathison, Richard P., "Mariner Mars 1964 Telemetry and Command System," *IEEE Spectrum*, pp. 76–84, July 1965.

9. Eberle, J. W., "An Adaptively Phased, Four Element Array of Thirty-Foot Parabolic Reflectors for Passive *(Echo)* Communication Systems," *IEEE Transactions on Antennas and Propagation*, pp. 169–176, March 1964.

10. Schrader, J. H., "A Phase-Lock Receiver for the Arraying of Independently Directed Antennas," *IEEE Transactions on Antennas and Propagation*, pp. 155–160, March 1964.

11. Drake, F. D., *Self Phasing Radio Telescope Arrays*, CRSR 179, Center for Radiophysics and Space Research, Cornell University, Ithica, New York, September 1964.

12. Schmuecker, J. D., and Wilson, James N., "Structural and Mechanical Design of Mariner Mars," *Astronautics and Aeronautics*, pp. 26–33, August 1965.

13. Rechtin, E., *Space Communications*, A. V. Balakrishnan, Ed., McGraw-Hill, New York, 1963, p. 28.

14. "U.S. Boosters for Aerospace Projects," *Space/Aeronautics*, pp. 88–89, January 1964.

15. (U) *Study of DOD and NASA Launch Vehicle Requirements by the Launch Vehicle Panel of the Aeronautics and Astronautics Coordinating Board*, NASA, Washington, D. C., December 1964. (Confidential)

16. Colby, Starr J., "Bringing Economies to Space Program Hardware," *Astronautics and Aeronautics*, pp. 68–72, August 1965.

17. Li, Tingye, "A Study of Spherical Reflectors as Wide Angle Scanning Antennas," *IRE Transactions on Antennas and Propagation*, Vol. AP-7, No. 3, pp. 223–226, July 1959.

18. Kay, A. F., "Design of Line Feed for World's Largest Aperture Antenna," *Electronics* Vol. 34, pp. 46–47, July 1961.

19. Schell, A. C., *An Analysis of the Effects Caused by Interstices on a Multiple Plate Antenna*, AFCRL Technical Memo CRRD-81, February 1963.

20. Schell, A. C., "A Multiplate Radio Astronomy Antenna," *Nerem Record*, pp. 196–197, 1963.

ACKNOWLEDGMENT